Fiber Reinforced Concrete
Exodus 5:6,

And Pharaoh commanded the same day the taskmasters of the people, and their officers, saying,

Ye shall no more give the people straw to make brick, as heretofore: let them go and gather straw for themselves.

Egyptians used straw to reinforce mud bricks, but there is evidence that asbestos fiber was used to reinforce clay posts about 5000 years ago.
Even though the market for fiber reinforced concrete is still small compared to the overall production of concrete, in North America there has been an yearly growth rate of 20% and that the worldwide yearly consumption of fibers used in concrete is 300,000 tons.
Classification according to volume fraction

- **Low volume fraction** (<1%)
- **Moderate volume fraction** (between 1 and 2%)
- **High volume fraction** (greater than 2)
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Low volume fraction

- The fibers are used to reduce shrinkage cracking. These fibers are used in slabs and pavements that have large exposed surface leading to high shrinkage crack.

- Disperse fibers offer various advantages of steel bars and wiremesh to reduce shrinkage cracks:
  - (a) the fibers are uniformly distributed in three-dimensions making an efficient load distribution;
  - (b) the fibers are less sensitive to corrosion than the reinforcing steel bars,
  - (c) the fibers can reduce the labor cost of placing the bars and wiremesh.
The presence of fibers at this volume fraction increase the modulus of rupture, fracture toughness, and impact resistance. These composite are used in construction methods such as shotcrete and in structures that require energy absorption capability, improved capacity against delamination, spalling, and fatigue.
The fibers used at this level lead to strain-hardening of the composites. Because of this improved behavior, these composites are often referred as high-performance fiber-reinforced composites (HPFRC). In the last decade, even better composites were developed and are referred as ultra-high-performance fiber-reinforced concretes (UHPFRC).
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Toughening Mechanism

(a) Graph showing Toughness and Strength in Relation to Plain Concrete vs. % Volume of Fibers. The graph illustrates the relationship between the percentage of fibers and the toughness and strength of concrete.

(b) Table showing the effect of aspect ratio and type reinforcement on toughness and strength.

<table>
<thead>
<tr>
<th>Type reinforcement</th>
<th>Aspect ratio L/d</th>
<th>Relative Strength</th>
<th>Relative Toughness</th>
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<td>Plain concrete</td>
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<tr>
<td>Random fiber</td>
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<td>1.70</td>
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<tr>
<td></td>
<td>100</td>
<td>1.50</td>
<td>8.5</td>
</tr>
</tbody>
</table>

Effect of aspect ratio:

- Plain concrete: 0
- Random fiber: 25, 50, 75, 100

Effect of type reinforcement:

- Conventional tensile bar: 3.15
- Random fibers: 75, 1.00

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The composite will carry increasing loads after the first cracking of the matrix if the pull-out resistance of the fibers at the first crack is greater than the load at first cracking;

At the cracked section, the matrix does not resist any tension and the fibers carry the entire load taken by the composite.

With an increasing load on the composite, the fibers will tend to transfer the additional stress to the matrix through bond stresses. This process of multiple cracking will continue until either fibers fail or the accumulated local debonding will lead to fiber pull-out.
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According to the report by ACI Committee 554 the total energy absorbed in fiber debonding as measured by the area under the load-deflection curve before complete separation of a beam is at least 10 to 40 times higher for fiber-reinforced concrete than for plain concrete.

The magnitude of improvement in toughness is strongly influenced by fiber concentration and resistance of fibers to pull-out which, other factors, such as shape or surface texture.
From a material and structural point of view, there is a delicate balance in optimizing the bond between the fiber and the matrix.

If the fibers have a weak bond with the matrix, they can slip out at low loads and do not contribute very much to bridge the cracks. In this situation, the fibers do not increase the toughness of the system.

If the bond with the matrix is too strong, many of the fibers may break before they dissipate energy by sliding out. In this case, the fibers behave as non-active inclusions leading to only marginal improvement in the mechanical properties.
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Role of Fiber Size

- To bridge the large number of microcracks in the composite under load and to avoid large strain localization it is necessary to have a large number of short fibers. The uniform distribution of short fibers can increase the strength and ductility of the composite.

- Long fibers are needed to bridge discrete macrocracks at higher loads; however the volume fraction of long fibers can be much smaller than the volume fraction of short fibers. The presence of long fibers significantly reduces the workability of the mix.
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Fiber size

A: Effect of short fibers on the microcracking

B: Effect of long fibers on the macrocracking

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It is well known that the addition of any type of fibers to plain concrete reduces the workability.

Since fibers impart considerable stability to a fresh concrete mass, the slump cone test is not a good index of workability. For example, introduction of 1.5 volume percent steel or glass fibers to a concrete with 200 mm of slump is likely to reduce the slump of the mixture to about 25 mm, but the placeability of the concrete and its compactability under vibration may still be satisfactory.

Therefore, the Vebe test is considered more appropriate for evaluating the workability of fiber-reinforce concrete mixtures.
Vebe Test

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Inclusion of steel fibers in concrete has little effect on the modulus of elasticity, drying shrinkage, and compressive creep.

Tensile creep is reduced slightly, but flexural creep can be substantially reduced when very stiff carbon fibers are used.

However, in most studies, because of the low volume the fibers simply acted as rigid inclusions in the matrix, without producing much effect on the dimensional stability of the composite.
When well compacted and cured, concretes containing steel fibers seem to possess excellent durability as long as fibers remain protected by the cement paste.

In most environments, especially those containing chloride, surface rusting is inevitable but the fibers in the interior usually remain uncorroded.

Long-term tests of steel-fiber concrete durability at the Battelle Laboratories in Columbus, Ohio, showed minimum corrosion of fibers and no adverse effect after 7 years of exposure to deicing salt.
Glass Fibers

- Ordinary glass fiber cannot be used in portland cement mortars or concretes because of chemical attack by the alkaline cement paste.
- Zirconia and other alkali-resistant glass fibers possess better durability to alkaline environments, but even these are reported to show a gradual deterioration with time.
- Similarly, most natural fibers, such as cotton and wool, and many synthetic polymers suffer from lack of durability to the alkaline environment of the portland cement paste.
There is a new generation of high performance fiber-reinforced composites. In many of these materials the strength, toughness, and durability are significantly improved.
Researchers in Denmark created *Compact Reinforced Composites* using metal fibers, 6 mm long and 0.15 mm in diameter, and volume fractions in the range of 5 to 10%.

High frequency vibration is needed to obtain adequate compaction. These short fibers increase the tensile strength and toughness of the material.

The increase of strength is greater than the increase in ductility, therefore the structural design of large beams and slabs requires that a higher amount of reinforcing bars be used to take advantage of the composite.
The short fibers are an efficient mechanism of crack control around the reinforcing bars. The final cost of the structure will be much higher than if the structure would be made by traditional methods, therefore the use of compact reinforced composites is mainly justified when the structure requires special behavior, such as high impact resistance or very high mechanical properties.
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Reactive Powder Concrete (RPC)

- Investigators in France by adding metal fibers, 13 mm long and 0.15 mm in diameter, with a maximum volume fraction of 2.5%.
- This composite uses fibers that are twice as long as the compact reinforced composites therefore, because of workability limitations, cannot incorporate the same volume fraction of fibers.
- The smaller volume fraction results in a smaller increase in the tensile strength of the concrete. Commercial versions of this product have further improved the strength of the matrix, chemically treated the surface of the fiber, and added microfibers.
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Another view
Slurry-Infiltrated-fibered concrete (SIFCON)

- The processing of this composite consists in placing the fibers in a formwork and then infiltrating a high w/c ratio mortar slurry to coat the fibers.
- Compressive and tensile strengths up to 120 MPa and 40 MPa, respectively have been obtained. Modulus of rupture up 90 MPa and shear strength up to 28 MPa have been also reported.
- In direct tension along the direction of the fibers, the material shows a very ductile response. This composite has been used in pavements slabs, and repair.
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The ultra high-ductility of this composite, 3-7%, was obtained by optimizing the interactions between fiber, matrix and its interface.

Mathematical models were developed so that a small volume fraction of 2% was able to provide the large ductility.

The material has a very high stain capacity and toughness and controlled crack propagation.
The manufacturing of ECC can be done by normal casting or by extrusion. By using an optimum amount of superplasticizer and non-ionic polymer with steric action, it was possible to obtain self-compacting casting. Experimental results with extruded pipes indicate that the system has a plastic yielding behavior instead of the typical brittle fracture exhibited when plain concrete is used.
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Engineered Cementitious Composite (EEC)

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Researchers the Laboratoire Central des Ponts et Chausées (France) proposed to combine short and long fibers to increase the tensile strength, the bearing capacity, and the ductility.

With this blend, good workability was achieved with fiber volume fractions up to 7%.

One typical combination of fibers is 5% straight drawn steel fibers, 5-mm long and 0.25 mm in diameter, and 2% hooked-end drawn steel fibers, 25-mm long and 0.3 mm in diameter.